Evaluation of Uniformity Coefficients for Sprinkler Irrigation Systems under Different Field Conditions in Kurdistan Province (Northwest of Iran)

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Abstract: In the past few decades, several coefficients of uniformity were developed to express the uniformity of water distribution for different sprinkler irrigation systems. Christiansen's uniformity coefficient seems to be the most popular uniformity coefficient used by researchers on the global scale. However, more coefficients have also been proposed by other researchers. Therefore, this study focused on evaluating different uniformity coefficients proposed and on investigating the effects of field conditions on the results obtained by means of those coefficients. In doing so, sprinkler uniformity tests were conducted by using rain-gauge in order to measure the uniformity coefficients of ten fields irrigated by solid set sprinkler irrigation systems in Dehgolan Plain located in the Kurdistan Province, northwest of Iran. All fields selected differed in prevailing conditions such as the wind speed, size and type of nozzle, raiser height, operating pressure and sprinklers spacing. The coefficient of uniformity for each field was computed using the equations proposed by Christiansen (1942), Hawaiian Cane Society Specialists Hart and Reynolds (1965), Wilcox and Swailes (1947), Karmeli (1978), Criddle et al. (1956), Benami and Hore (1964), and Beale (1966). Data analysis was performed using the general linear model procedure of Statistical Analysis System Software. The results indicated that should not the field effect be considered in the statistical model, significant differences ($P < 0.05$) would be observed between the aforesaid coefficients; however, by considering the field effect in the statistical model, no significant differences ($P > 0.05$) would be observed. The results of this study conclusively indicated that the application of various coefficients of uniformity depends on the field conditions and as any specific coefficient of uniformity is suitable only for specific field conditions.

Keywords: coefficient of uniformity; Christiansen equation; Iran; solid set; sprinkler irrigation

The uniformity of water application in a sprinkler irrigation system is an important aspect of the system performance (Solomon 1979). The performance of a sprinkler irrigation system is often evaluated based on water uniformity coefficients collected in an array of measuring devices (i. e., rain-gauge) (Topak *et al.* 2005). Such system requires a minimum value of uniformity to be considered as acceptable by the end users. Keller and Bliesner (1990) classified the irrigation uniformity in solid set systems as "low" when the Christiansen's coefficient of uniformity was below 84%. A sprinkler water distribution pattern depends on the system design parameters such as: the sprinkler spacing, operating pressure, nozzle diameter, and environmental variables such as: wind speed and direction (Keller & Bliesner 1990). Several authors have reported the wind to be the main environmental variable affecting the sprinkler performance (Solomon 1979; Kincaid *et al.* 1996; Dechmi *et al.* 2003).

The frequency distribution of the applied water can be assumed as normal and uniform functions (Anyoji & Wu 1994; Mantovani *et al.* 1995; Li 1998). The sprinkler irrigation distribution patterns have been characterised by various statistical uniformity coefficients (Karmeli 1978) and various coefficients of uniformity (*CU*s) have been developed over the past decades (Al-Ghobari 2006). Christiansen's coefficient of uniformity (Christiansen 1942) was first used to introduce a uniformity coefficient to the sprinkler system (Karmeli 1978). The coefficient is presently widely used by researches on the global scale and has been applied as a proven criterion to define water distribution uniformity (Karmeli 1978; Topak *et al.* 2005). The coefficient is derived from rain-gauge data based on the assumption that the rain-gauge represent the same area and is a measure of absolute difference from the mean divided by the mean:

$$CU = 100\left(1 - \frac{\sum_{i=1}^{n}|X_i - \mu|}{\sum_{i=1}^{n} X_i}\right) \quad (1)$$

where:
n – number of the depth measurements of the water applied, each representing an equal irrigated area
X_i – measured application depth (L)
μ – mean application depths of (L)
CU – coefficient of uniformity (%)

When the CU value is approximately 70% or higher, the approximation depths from a rain-gauge evaluation tend to follow a normal distribution. In this case, when the mean application depth, μ, is equal to the required net application depth, d_n, 50% of the irrigated area will be under-irrigated while the remaining 50% will be over-irrigated (or "adequately irrigated"). This is due to the fact that the normal distribution is symmetrical about the mean value (Merkley 2001).

Wilcox and Swailes (1947) used the same method used by Christiansen (1942), except that they used squares of the deviations from the mean instead of the deviations themselves. Their proposed equation is as follows:

$$U = 100\left(1 - \frac{\sigma}{\mu}\right) \quad (2)$$

where:
U – uniformity coefficient (%)
σ – standard deviation of total depths of water (L)
μ – mean application depth (L)

The coefficients of uniformity obtained in this manner are not as high as those in which the deviations from the mean are used such as in Christiansen's equation.

Hart and Reynolds (1965) proposed "distribution efficiency", DE_{pa}, a value based on numerical integrations of the normal distribution function while DE_{pa} is determined by first selecting a target *CU* and a target "percent area adequately irrigated", *Pa*, where 50% ≤ *Pa* < 100% (which is a logical range for *Pa*). Should the normal distribution be assumed 70% ≤ *CU* < 100%, and

$$\sum_{i=1}^{n}|X_i - \mu| \cong n\sigma\sqrt{2/\pi} \quad (3)$$

where:
σ – standard deviation of all depth measurements (L)

Substituting Eq. (3) into Eq. (1),

$$CU \cong 100\left[1 - \left(\frac{0.798\sigma}{\mu}\right)\right] \quad (4)$$

Criddle *et al.* (1956) and Beale and Howell (1966) also used the concepts of the deviations of the mean, like Christiansen (1942); however, Criddle *et al.* (1956) limited their equation to the lowest quarter depths of water while Beale limited the equation to the highest ones. Criddle *et al.* (1956) proposed their equation as follows:

$$CU = 100\left(1 - \frac{\sum_{i=1}^{\frac{n}{4}}|X_i - \mu|}{\mu \times \frac{n}{4}}\right) \quad (5)$$

Beale & Howell (1966) also proposed an equation as follows:

$$CU = 100\left(1 - \frac{\sum_{i=\frac{3}{4}n+1}^{n}|X_i - \mu|}{\mu \times \frac{n}{4}}\right) \quad (6)$$

Karmeli (1978) reported that the uniform distribution was an acceptable form to represent the sprinkler water distribution for stationary systems. He expressed the coefficient of uniformity as:

$$CU = 100\,[1 - 0.5(X_{max} - \mu)] \quad (7)$$

This equation is only valid for the values of *CU* higher than 50%.

Benami and Hore (1964) introduced their uniformity coefficient as "*A*" coefficient. Their equation is as follows:

$$A = 166\left(\frac{N_a}{N_b}\right)\left(\frac{2T_b + D_b M_b}{2T_a + D_a M_a}\right) \quad (8)$$

where:

A – uniformity coefficient (%)

M_a, M_b – means of the measured application depths which are greater and smaller than the overall mean application depths (L), respectively

N_a, N_b – numbers of the measured application depths which are greater and smaller than the overall mean application depths, respectively

T_a, T_b – sums of the measured application depths which are greater and smaller than M_a and M_b (L), respectively

D_a, D_b – differences between the numbers of the measured application depths which are greater and smaller than M_a and M_b, respectively

Merriam and Keller (1978) defined their "distribution uniformity coefficient" as follows:

$$DU = 100\left(\frac{D_{lq}}{\mu}\right) \quad (9)$$

where:

DU – distribution uniformity (%)

D_{lq} – mean of the lowest one-quarter of the measured depths (L)

Hawaiian Cane Society Specialists (cited by Merriam and Keller 1978) also proposed their uniformity coefficient as follows:

$$CU = \left[1 - \left(\frac{2}{\pi}\right)^{0.5}\left(\frac{\sigma}{\mu}\right)\right] \times 100 \quad (10)$$

As stated previously, different researchers have used various concepts to express the coefficients of uniformity, hence the equations lead to different results in the expression of the distributed water uniformity in the same fields. The main objective of this study was to evaluate different uniformity coefficients proposed and investigate the effects of the field conditions on the end results obtained.

MATERIALS AND METHODS

The field experiments were conducted during April–June 2008 on ten farmlands located in the Dehgolan Plain of the Kurdistan Province, northwest Iran from 47°07' to 47°36'E and from 25°02' to 25°28'N. This region has a mean annual precipitation of 340 mm. Figure 1 show the location of the Kurdistan Province and Dehgolan Plain.

The lands were irrigated by solid set sprinkler irrigation systems. The sprinkler uniformity tests were conducted using rain-gauge for uniformity coefficients measuring (Figure 2). The rain-gauge had a diameter of 96 mm and a height of 120 mm. The irrigation assessment was carried out

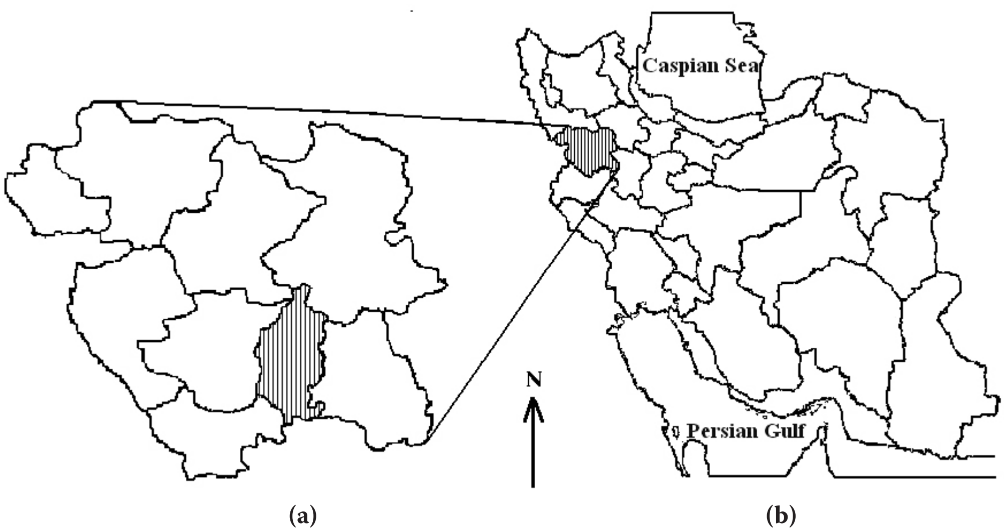

Figure 1. (a) Location of Dehgolan plain on Kurdistan province map and location of Kurdistan province on Iran map (b)

Table 1. The experimental fields meteorological data and other details

Experimental fields	Average		Sprinkler		Average sprinkler			Sprinkler type	Nozzle diameters (mm)
	wind speed (m/s)	temperature (°C)	spacing (m)	height (m)	pressure (kPa)	discharge (l/s)	intensity (mm/h)		
F 1	5.1	16	S25 × 25	0.8	370	1.8	10.37	PEROT (ZK30)	8 and 3.5
F 2	7.2	25	R25 × 28	0.9	340	1.85	9.51	AMBO	8 and 7
F 3	6.5	21	S25 × 25	1	340	2	11.52	AMBO	8 and 7
F 4	2.9	23	S26 × 26	1	200	1.66	8.91	PEROT (ZM22)	10 and 3.5
F 5	5.8	17	R23 × 25	0.9	330	1.73	10.83	AMBO	8 and 7
F 6	3.6	17	S25 × 25	1	450	2.35	13.54	AMBO	8 and 7
F 7	4.3	26	R24 × 25	1.3	350	2	12	AMBO	8 and 7
F 8	2.2	26	R25 × 28	1	340	2	10.11	AMBO	8 and 7
F 9	2.9	25	S25 × 25	1	370	2.2	12.67	AMBO	8 and 7
F 10	5.1	20	R24 × 21	0.9	260	1.42	10.14	PEROT (ZK30)	8 and 3.5

to measure the water distribution on the surface following the methodology proposed by Merriam and Keller (1978). In each field, the coefficient of uniformity was computed using the equations proposed by Christiansen (1942), Hawaiian cane society specialists (cited in Merriam & Keller 1978), Wilcox and Swailes (1947), Criddle *et al.* (1956), Benami and Hore (1964), Hart and Reynolds (1965), Beale & Howell (1966), and Karmeli (1978). Data analysis was performed using the general linear model (GLM) procedure of Statistical Analysis System (SAS 2003) software. Two statistical models were used to compare the results of different uniformity coefficients. The first statistical model was as below:

$$y_{ij} = \mu + C_i + e_{ij} \qquad (11)$$

where:
y_{ij} – measured value
μ – overall mean
C_i – effect of the uniformity coefficient
e_{ij} – random error with mean 0 and variance σ^2

The field meteorological and other data such as: the wind speed, size and type of nozzle, raiser height, operating pressure, and sprinkler spacing

Figure 2. One example of sprinkler uniformity test using rain-gauge for measuring uniformity coefficients of selected farms; rain-gauge had a diameter of 96 mm and a height of 120 mm

Table 2. Comparison of the uniformity coefficients means (in %) using the first statistical model

SEM	Benami & Hore	Hawaian cane society specialist	Hart & Reynolds	Christiansen	Wilcox & Swailes	Karmeli	Merriam & Keller	Criddle *et al.*	Beale
1.66	73.5^{a}	67.3^{ab}	67.3^{ab}	66.5^{ab}	59.1^{bc}	51.2^{cd}	51^{cd}	49.9^{cd}	42.5^{d}

SEM – standard error of the mean; different letters – meaningful levels

were not similar for all farms (Table 1); thus, the second statistical model was used as follows:

$$y_{ij} = \mu + C_i + F_j + e_{ijk} \quad (12)$$

where:

y_{ijk} – measured value

F_j – field effect

e_{ijk} – random error with mean 0 and variance σ^2

Finally, the data mean differences were determined using Duncan test at a 95% confidence level; and then the data signification levels were reported as the means of treatments with the standard error means.

RESULTS

The results of computing different *CU*s for all fields are presented in Figure 3. As Figure 3 shows, the horizontal axis represents different *CU*s and the vertical axis represents their values in percentages. Ten existing series of data in this figure represent the values of various coefficients of uniformity for ten experimental farms.

The results of this study using the first statistical model (Eq. (11)), indicated that significant differences ($P < 0.05$) exist in the above given coefficients. Table 2 also shows the levels of differences and the maximum and minimum values for the mean of *CU*s was obtained with Benami and Hore and Beale equations, respectively.

The results of the second statistical analysis showed that there were no significant differences ($P > 0.05$) in the uniformity coefficients.

DISCUSSION

The results of computing different *CU*s for experimental farms are shown in Figure 3. This figure shows the general trend of uniformity coefficient variations for each of the experimental farms.

The results of this study, using the first statistical model (Eq. (11)), indicated that significant differences ($P < 0.05$) existed between the coefficients stated.

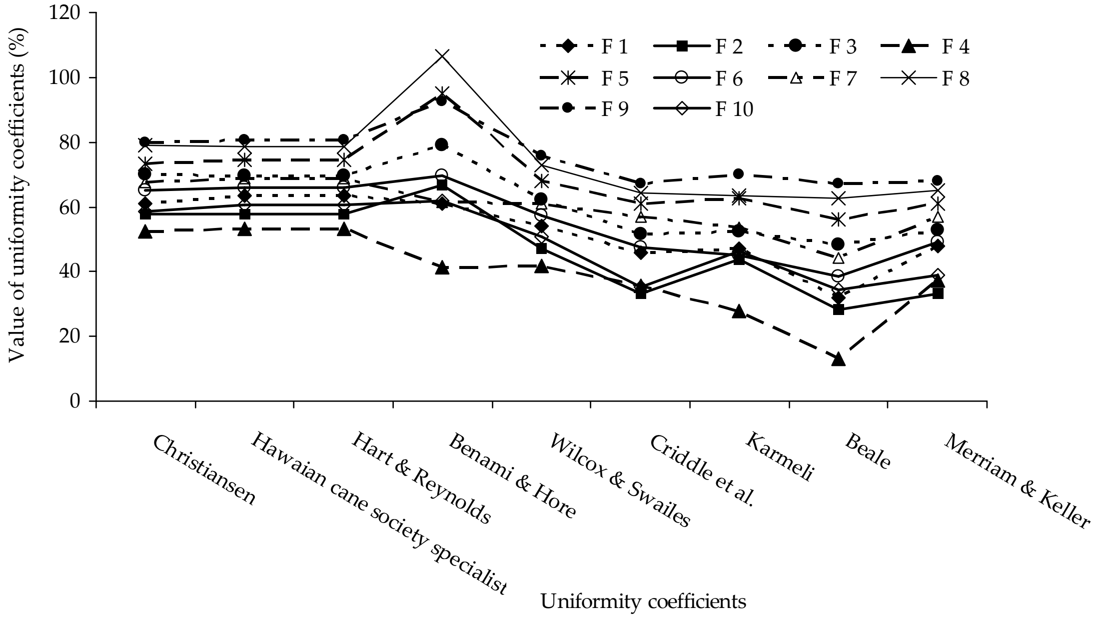

Figure 3. The results of computing different *CU*s for all farms; this figure shows the general trend of uniformity coefficient variations for each of the experimental farms

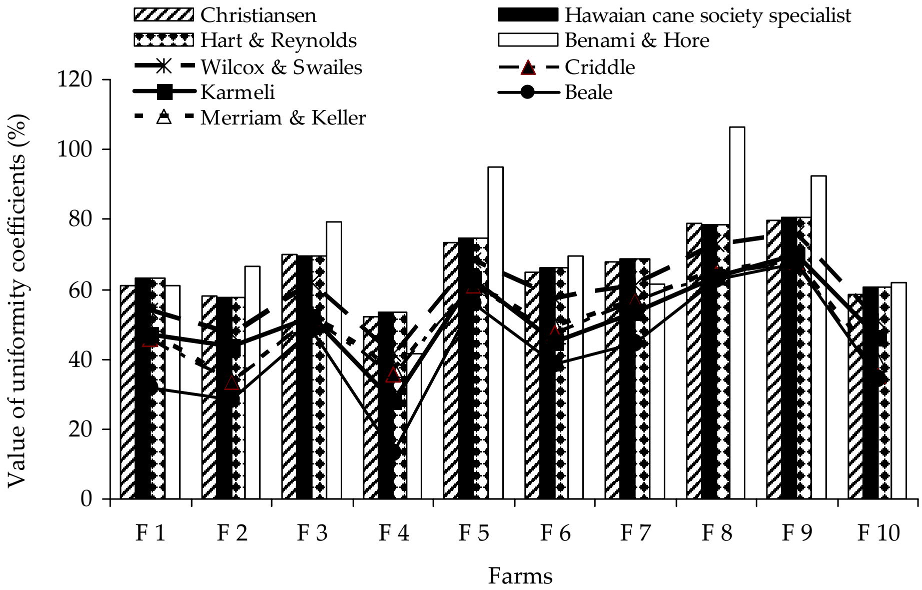

Figure 4. Comparison of different uniformity coefficients for each of the experimental farms; using Benami and Hore's equation resulted in the coefficient of uniformity above than 100% for one of the farms (F 8)

Table 2 shows the levels of these differences. Also, this table shows that the maximum and minimum for the mean of *CU*s in this study were obtained with Benami and Hore and Beale equations respectively.

The calculated values of CUs are also shown in Figure 4. This figure clearly shows that the equations of Christiansen, Hart and Reynolds, and Hawaian cane society specialist provided very close results for each of the experimental fields. However, the equation by Benami and Hore produced the results in few cases (F 1, F 6, and F 10) while the equation resulted in completely different results in other fields. This equation computed the coefficient of uniformity above 100% for one of the experimental fields (F 8).

Solomon (1979) reported that the coefficient of uniformity depends on the design variables of the system (ie the sprinkler make, size and type of nozzle, pressure and sprinkler spacing), and the main uncontrollable variable, the wind speed. However, the field conditions were not similar for all of the experimental farms. Therefore, the second statistical analysis was performed using the second statistical model (Eq. (12)) in order to compare the means of the uniformity coefficients. In this model, to reduce the existing errors, the field conditions effect was taken into account as F_j term.

The results of the second statistical analysis showed that there were no significant differences ($P > 0.05$) between the uniformity coefficients. Based on the comparison of the results obtained from the two statistical analyses mentioned, one can infer that the existing significant differences between the uniformity coefficients in the first statistical analysis were mainly due to the varying field conditions.

Finally, the results of this study emphasised the fact that various coefficients of uniformity depend on the field conditions and one is not allowed to use a given uniformity coefficient for any other field conditions.

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